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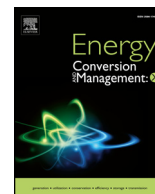
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The impact of disruptive powertrain technologies on energy consumption and carbon dioxide emissions from heavy-duty vehicles

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ABSTRACT

Minimising tailpipe emissions and the decarbonisation of transport in a cost effective way remains a major objective for policymakers and vehicle manufacturers. Current trends are rapidly evolving but appear to be moving towards solutions in which vehicles which are increasingly electrified. As a result we will see a greater linkage between the wider energy system and the transportation sector resulting in a more complex and mutual dependency. At the same time, major investments into technological innovation across both sectors are yielding rapid advancements into on-board energy storage and more compact/lightweight on-board electricity generators.

In the absence of sufficient technical data on such technology, holistic evaluations of the future transportation sector and its energy sources have not considered the impact of a new generation of innovation in propulsion technologies. In this paper, the potential impact of a number of novel powertrain technologies are evaluated and presented. The analysis considers heavy duty vehicles with conventional reciprocating engines powered by diesel and hydrogen, hybrid and battery electric vehicles and vehicles powered by hydrogen fuel cells, and free-piston engine generators (FPEGs). The benefits are compared for each technology to meet the expectations of representative medium and heavy-duty vehicle drivers. Analysis is presented in terms of vehicle type, vehicle duty cycle, fuel economy, greenhouse gas (GHG) emissions, impact on the vehicle *etc.*

The work shows that the underpinning energy vector and its primary energy source are the most significant factor for reducing primary energy consumption and net CO₂ emissions. Indeed, while an HGV with a BEV powertrain offers no direct tailpipe emissions, it produces significantly worse lifecycle CO₂ emissions than a conventional diesel powertrain. Even with a de-carbonised electricity system (100 g CO₂/kWh), CO₂ emissions are similar to a conventional Diesel fuelled HGV. For the HGV sector, range is key to operator acceptability of new powertrain technologies. This analysis has shown that cumulative benefits of improved electrical powertrains, on-board storage, efficiency improvements and vehicle design in 2025 and 2035 mean that hydrogen and electric fuelled vehicles can be competitive on gravimetric and volumetric density. Overall, the work demonstrates that presently there is no common powertrain solution appropriate for all vehicle types but how subtle improvements at a vehicle component level can have significant impact on the design choices for the wider energy system.

1. Introduction

In recent decades, worldwide consumption of conventional road-based transportation fuels (gasoline and diesel) has increased by around 1.5% per year [1]. This increase has been fundamental to the advancement of worldwide living standards, nevertheless our lifestyles

are now threatened by a combination of factors including climate change, vehicle tailpipe emissions, decline of conventional oil extraction sources and moves toward alternative and more renewable energy sector. In recent years, Low Emission Zones (LEZs) have been put in place or approved throughout Europe, with the United Kingdom, France and Germany all announcing that pure internal combustion

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engine (ICE) technology will be banned in the 2040 timescale [2].

As a result, various pathways to decarbonise the vehicle powertrain technology (and corresponding energy carriers) have been proposed including electric vehicles (electricity), fuel cells and internal combustion engines (hydrogen) and internal combustion engines (oxygenated hydrocarbons) etc.. Through a series of industry and academic consultations, the Advanced Propulsion Centre [3] has developed a consensus view of the future development and application of key powertrain technologies through consultation with technology developers, vehicle manufacturers and funders resulting in an increasingly complex series of technology roadmaps [3]. Increasingly electrified powertrains are now proving to be a promising way forward with a growing number of technology combinations now possible. Nevertheless, the demands of each driver or journey are very different and electrified vehicles may not offer the required range to complete all required journeys without a stop and recharge. Whilst this may well prove a frustrating experience for passenger vehicles, it would represent an asset off the road and a loss in earnings for commercial goods distributors.

However, the conventional liquid hydrocarbon fuelled internal combustion engine still remains the overwhelmingly dominant solution due to a combination of highly favourable economic and technological factors driven by a century of mass-scale manufacture and low-cost primary energy. Furthermore, the energy density (volumetric and gravimetric) of the on-board storage and energy conversion devices make them highly practical for vehicles with long distance, high energy duty cycles with minimal refuelling times.

The urgent need to overcome the challenge of range has meant that the underpinning powertrain architecture for vehicles is evolving rapidly, as shown in Fig. 1 there are now multiple options beyond the conventional Internal Combustion Engine (ICE). Hybrid electric (P) HEV and Range-extender electric vehicles (REEVs) are seen as promising solutions for overcoming this issue. In addition, a basic battery electric vehicle (BEV) might also support a removable on-board electrical generator which is used to charge the battery during the journey. First generation range extenders (REs) are seen as conventional reciprocating internal combustion engines with attached electrical generators examples such as Lotus [4] and Mahle Powertrain [5], second generation REs are more integrated electro-mechanically integrated solutions with third generation range extenders a wholly integrated electromechanical solution including fuel cells, free-piston engines, rotary engines etc.. As a result, there are aggressive projections for the uptake of REEVs ranging from 8% to 30% [6] [7] of new vehicle sales in 2030. Hydrogen Fuel Cell vehicles (H2FC) can also present an opportunity to offer vehicle range suitable for a heavy duty vehicle with refuelling times similar to current Diesel vehicles. Scarcity of hydrogen refuelling infrastructure may limit uptake of this technology, however back to base refuelling and on board hydrogen production (using technologies such as on board reforming [8]) could support greater adoption of fuel cell vehicles.

In the literature, there are a range of “Well-to-Wheel studies” and “techno-economic, energy and environmental impact assessment studies” on alternative fuels and vehicle powertrain architectures with different time horizons. Most of those studies were confined to industrialised countries, with an emphasis on specific country or region. Some of the key research representative of different regions such as America, EU, UK, global with long time horizons are summarised below.

In 2008 Massachusetts Institute of Technology (MIT) published a report “On the road in 2035”, which was a successor to their 2000 report, “On the Road in 2020” [9]. The report summarised the technologies of light-duty vehicles and fuels that could be developed and commercialised during the next 25 years, and compared the options for reducing fuel consumption, especially fuels from petroleum and greenhouse gas (GHG) emissions, during the production and use of both fuels and vehicles. Spark-ignition, compression-ignition, gasoline

hybrid-electric, plug-in hybrid electric, battery electric, fuel cell vehicles were selected, and the effect of those technologies on the performance, cost, and lifecycle emission of individual vehicles were assessed. Their influence to the total on-the-road fleet was also considered. It was concluded that a 30%–50% reduction in fuel consumption was feasible over the next 30 years, while no single technology development or alternative fuel can solve the problems of growing transportation fuel use and GHG emissions. In the short-term, improved spark-ignition and compression-ignition engines and transmissions, gasoline hybrids, and reductions in vehicles weight and drag were expected with an estimation of \$1500–\$4500 increase in vehicle costs. Over the longer term, plug-in hybrids and later still, hydrogen fuel cells may enter the fleet in numbers sufficient to have significant an impact on fuel use and emissions.

The report “The Energy Evolution: An Analysis of Alternative Vehicles and Fuels to 2100” published by the National Hydrogen Association in America compared more than 15 of the most promising distinct fuel and vehicle alternatives over a 100 year period, in scenarios where one fuel and vehicle alternative becomes dominant in the vehicle mix over time [10]. This comprehensive study assessed the environmental sustainability, energy security and economic vitality of each alternative technology, in the context of America’s passenger vehicle transportation system. The report concluded that the best scenario for America would be a scenario in which hydrogen-powered fuel cell vehicles dominate the marketplace, as hydrogen used in a fuel cell vehicle was founded to be the only transportation fuel that could, in conjunction with hybrids, plug-in hybrids and biofuel, reduce GHG pollution by 80% below 1990 levels and simultaneously. Meanwhile, the cost of building a hydrogen fuelling infra-structure was reported to be affordable, and all the hydrogen needed for hydrogen-powered vehicles could be produced from domestic energy sources.

The International Energy Agency (IEA) published a report “Transport, Energy and CO₂, Moving toward Sustainability” in 2009, which provided a broader study as the transport sector was analysed on a global scale [11]. The IEA model adopted both historical data and projections to 2050, and contained a large amount of techno-economic data for all main type of road vehicles as well as non-road transport modes, which could calculate costs, energy consumption, and GHG pollutions. The results suggested that, by aggressively deploying incremental fuel economy technologies and hybridisation, a 50% reduction of fuel use and CO₂ emissions per km from the global stock of passenger cars would be achieved by 2050. Alternative, low-carbon fuels and vehicles, such as PHEVs, BEVs, FCVs, and advanced biofuels were necessary to be introduced, as in principle, any of these technologies could lead to significant reductions of fuel use and GHG pollutions. However, each one of those technologies was reported to face barriers, especially the cost in the short to medium term. It was argued that FCVs were a disruptive technology, and their large-scale application faced higher barriers than BEVs, for which a more evolutionary pathway was available via HEVs and PHEVs.

McKinsey & Company conducted a study, “A portfolio of power-trains for Europe: a fact-based analysis”, to evaluate the role of BEV, PHEV, and FCEV in the Europe by 2050 [12]. Several companies and organisations participated in this study, including BMW AG, Daimler AG, Ford, etc., and this study was based on industry data provided by them. Alternative fuel and powertrain options were compared for passenger cars from an economic, performance and sustainability point of view, and different passenger car sizes were considered, representative of 75% of the passenger car market in Europe. The results suggested that BEVs, PHEVs and FCEVs showed significant potential to reduce CO₂ and local pollution, assuming CO₂ reduction was performed at the production site. PHEVs were reported to be more economic than BEVs and FCEVs in the short term, which could reduce CO₂ considerably compared with ICEs on short trips or using biofuels, depending on availability. In the long term over the next 40 years, it was concluded that no single powertrain could satisfy all key criteria for economics, performance and

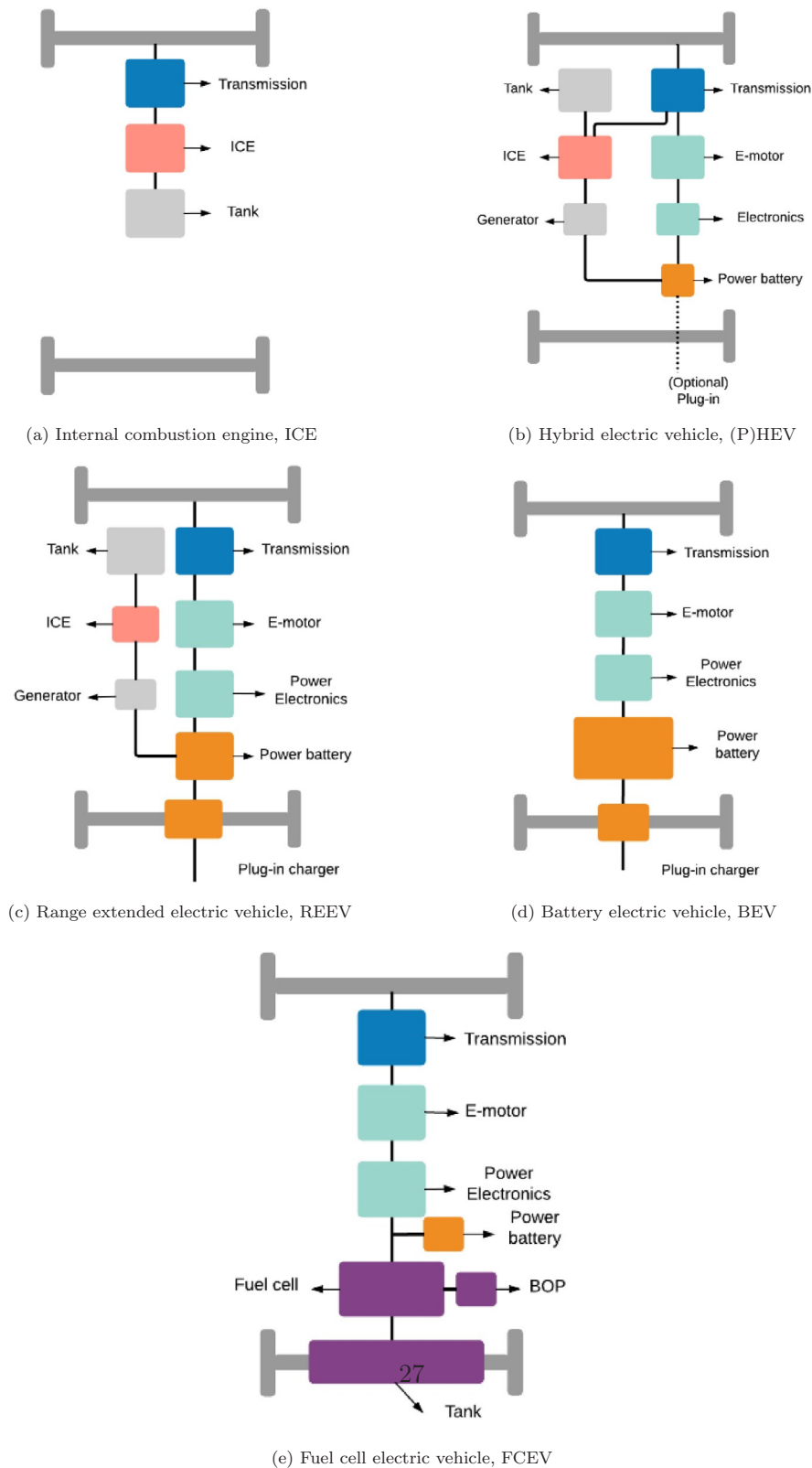


Fig. 1. Various powertrains architectures.

the environment. The world was reported to be likely to move from a single powertrain (ICE) to a portfolio of alternatives in which BEVs play a complementary role for smaller cars and shorter trips, and FCEVs to medium/larger cars and longer trips. PHEVs was reported to be an attractive alternative for short trips or where sustainability produced

biofuels are available.

Offer, et al. carried out a series of techno-economic studies to compare hydrogen fuel cell electric vehicles, battery electric vehicles, and hydrogen fuel cell plug-in hybrid electric vehicles in the UK using cost predictions for 2030 [13] [14] [15] [16]. Results showed that in

2030 FCEVs could achieve lifecycle cost parity with conventional gasoline vehicles. In the 2030 scenario, powertrain lifecycle costs of FCEVs range from \$7360 to \$22,580, while the BEV and FCHEV were reported to show similar range in lifecycle cost, which were \$6460 to \$11,420, and \$4310 to \$12,540 respectively. All vehicle options showed significant cost sensitivity to powertrain capital cost. The BEV and FCHEV were relatively insensitive to electricity costs, while FCHEV and FCEV were sensitive to hydrogen costs. There would be diminishing economic return for PHEVs with battery sizes of above 20 kWh, and the optimum size for a PHEV battery was reported to be between 5 to 15 kWh. Decreasing carbon dioxide emissions from electricity generation by 80% favours larger optimum battery sizes as long as carbon was priced, and would reduce emissions considerably.

In general terms, studies have broadly focused on passenger cars and have shown that hybrid and range extender technologies might be expected to have a relatively short lifetime as technology is rapidly evolving in this sector and that technologies such as lithium-ion batteries have become cheaper more rapidly than originally expected and as a result original projections for cost and/or range have been underestimated.

This study goes beyond the current state-of-the-art by considering the above in terms of heavy duty vehicles and how technology is expected to evolve. Specifically it focuses on the potential of multiple technologies for decarbonising the HD sector and their sensitivities. It presents a novel method to consider expert defined technology roadmaps to estimate future performance and to support data driven decision making across the whole vehicle development strategy. The outcomes indicate what performance may be possible in future generations of HD vehicle technology. Results show how vehicle fuel economy, energy use and emissions might be influenced in the years to come and the technologies required to deliver these.

2. Numerical methodology

A holistic evaluation of the vehicle, its performance and emissions requires the full consideration of the driver's expectations, the whole vehicle, any changes to the vehicle imposed when operating with a different powertrain, its journey and the providence of the fuel used in terms of its corresponding net CO₂ emissions (well-to-wheel) and supporting distribution infrastructure.

Reflecting these challenges, a summary of the numerical approach applied in this work is presented as follows:

1. *Vehicle operating duty-cycle or real-world journey:* An expected journey presented in terms of vehicle speed, v and road gradient, α as a function of time for the vehicle is defined. In this paper, the duty-cycle of the vehicle is represented by utilising internationally standardised cycles or measured real-world cycles [17].
2. *Vehicle model:* Vehicle size, design and operational parameters are defined including vehicle mass, m_v vehicle cross sectional area, A , rolling friction coefficient, c_r , aerodynamic discharge co-efficient, c_D etc.. These parameters are used to estimate the total energy, $E_{T,v}$ mean power, $P_{mean,v}$ and maximum power, $P_{max,v}$ at the road required to complete the defined duty cycle in Step 1.
3. *Main powertrain and transmission:* The on-board powertrain system is scaled to meet the mean power, $P_{mean,v}$, maximum power, $P_{max,v}$, total energy demand, $E_{T,v}$ of the vehicle over its duty cycle from Step 2. The corresponding efficiency, η_t , size, V_t and mass, m_t of the main powertrain and transmission are then computed. The required maximum power, $P_{max,t}$ and total energy demand, $E_{T,t}$ for the powertrain and transmission system are then evaluated.
4. *On-board energy conversion device:* Conventional ICE solutions are considered to be load following generators and scaled to meet the maximum required power, $P_{max,t}$ for the powertrain/transmission determined in Step 3. All other solutions are designed to meet the load following demand using an electrochemical battery which is

scaled to the maximum required power, $P_{max,t}$. If an on-board power generator is used, the electrochemical battery is charged continually using an on-board generator using the mean power demand, $P_{mean,t}$ for the powertrain/transmission from Step 3. The corresponding efficiency, η_g , size, V_g and mass, m_g of the power conversion device (and any auxiliary systems) are computed and used to determine the total energy demand, E_T for the vehicle to complete the duty-cycle/journey.

5. *On-board energy storage:* The energy capacity of on-board storage system is scaled to meet the total energy demand, E_T for the vehicle to complete the duty-cycle/journey determined in Step 4. The required energy capacity is used to determine the corresponding efficiency, η_s , size, V_s and mass, m_s of the on-board energy storage system (including the fuel). This can be used to determine the fuel consumption per km.
6. *Wider energy system:* When considering multiple energy vectors, its important to go beyond the consideration of tailpipe CO₂ emissions alone and focus on the emissions across the energy value chain and the impact of the technology on national energy systems which are in transition toward exploiting a greater proportion of more intermittent renewable energy sources. The total energy capacity for the on-board energy storage computed in Step 5 is used to determine the corresponding corresponding net CO₂ emissions and primary energy usage per km.

The underlying computation advances in a linear program from Step 1 through to Step 6. Nevertheless, some model derived parameters such as total vehicle mass (the sum of vehicle mass, transmission mass, on-board generator mass, energy storage mass etc.) are unknowns at Step 1. As such, Newton's Iterative Method is applied until the total vehicle mass achieves convergence, generally this is within ten iterations.

The evolution of HD vehicles and its underpinning technology as a function of time was also considered in this work. Whilst current vehicle and vehicle technology performance is known, its potential in the future can only be approximated. In order to estimate its evolution, expert-led consensus views of how the individual technologies roadmaps have been applied. In all cases, an external reference to a performance target, detailed study or expert working group have been identified to justify any assumptions.

The final stage of the work is to apply the model is used to explore HD vehicle performance with different on-board technologies. Vehicle size, mass, energy consumption and emissions are all determined to compare the different options. The sensitivities are all explored in depth. Lastly, future technology targets (or performance estimates) are explored to determine expected performance in 2025 and 2035.

2.1. Vehicle operating duty-cycle or real-world journey

As shown in Fig. 2, the vehicle is driven at the velocity, v [km] (assuming no wind conditions) over the road gradient, α . A time series of velocity, v and road gradient, α [radians] are user defined inputs to

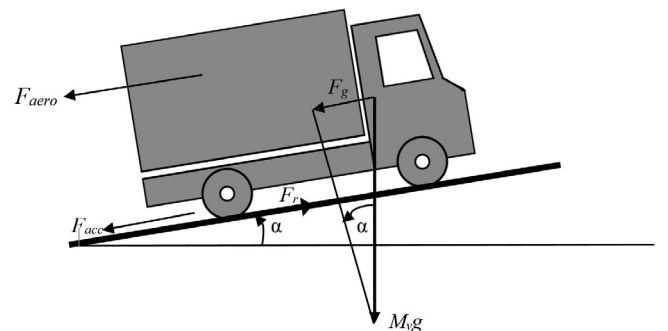


Fig. 2. Forces acting on the vehicle.

the model. Vehicle duty cycles vary depending on vehicle size (heavy/light duty) and application (freight transport/bus). In the absence of a real-world cycle which best represents all vehicle types, these time series profiles are represented by utilising internationally standardised cycles or measured real-world cycles [17]. The supplied cycle being repeated until the vehicle has reached its specified range, d_{range} [km].

2.2. Vehicle model

A vehicle of mass, m_v , is presented in Fig. 2. In this analysis we assume that the vehicle will behave according to Newton's second law as follows:

$$\delta m_v \frac{dv}{dt} = \sum F_t - \sum F_{tr} \quad (1)$$

where δ is a number greater than one to account for rotating inertia, $\sum F_t$ is the total tractive effort of the vehicle and $\sum F_{tr}$ is the sum of all vehicle resistance forces.

$$\sum F_{tr} = F_r + F_{aero} + F_{gr} + F_{acc} \quad (2)$$

where F_r , F_{aero} , F_{gr} and F_{acc} represent the forces associated with rolling resistance, aerodynamic resistance, grade resistance and acceleration respectively.

2.2.1. Rolling resistance

The rolling resistance force, F_r can be approximated as

$$F_r = c_r M_v g \cos \alpha \quad (3)$$

where the coefficient, c_r is the rolling friction coefficient of the order of 0.01.

2.2.2. Aerodynamic resistance

The aerodynamic resistance force, F_{aero} is exerted on the centre of aerodynamic pressure and can be approximated as:

$$F_{aero} = \frac{1}{2} \rho_{air} c_D A v^2 \quad (4)$$

where ρ_{air} is the density of air, c_D is the coefficient of drag of the vehicle, A is the cross-sectional area of the vehicle and v is the velocity of the vehicle (assuming no wind conditions).

2.2.3. Grade resistance

The grade resistance force, F_{gr} is zero when driving on flat surface (which is generally the case in standard tests). However, with a gradient this is expressed as follows

$$F_g = m_v g \sin \alpha. \quad (5)$$

where g is the gravitational constant.

2.2.4. Acceleration resistance

The acceleration force, F_{acc} is approximated according to the following expression:

$$F_{acc} = \delta m_v \frac{dv}{dt}. \quad (6)$$

2.2.5. Vehicle mass

The total mass of the vehicle, m_v is the base vehicle plus all on-board systems associated with the powertrain and on-board storage.

$$m_v = m_{base} + m_t + m_g + m_s \quad (7)$$

where m_{base} , m_t , m_g and m_s represent the mass of the base vehicle unit, transmission/powertrain, on-board power generation device and storage (including fuel) systems respectively.

2.3. Main powertrain and transmission

The underpinning powertrain architecture for vehicles is evolving rapidly, the most common examples are presented in Fig. 1.

The mass, m_t and size, V_t respectively for the powertrain and transmission system were obtained by summing the respective masses and sizes of the required components for the system. The cumulative mass and size of the individual components were determined by using the gravimetric and volumetric power densities at the required maximum power output of the powertrain, $P_{max,t}$.

The overall transmission efficiency, η_t was determined as the product of the component efficiencies across the powertrain/transmission system.

2.4. On-board energy conversion device

The mass, m_g and size, V_g for the on-board generator were obtained by summing the respective masses and sizes of the required sub-components for the system. The cumulative mass and size of the individual components were determined by using the gravimetric and volumetric power densities at the required mean power output of the powertrain, $P_{mean,t}$.

The overall energy conversion device efficiency, η_g was determined as the product of the component efficiencies across the powertrain/transmission system.

2.5. On-board energy storage

The mass, m_s and size, V_s for the on-board energy storage system were obtained by summing the respective masses and sizes of the required sub-components. The cumulative mass and size of the individual components were determined by using the gravimetric and volumetric energy storage device densities at the required total energy storage capacity, E_T .

2.6. Wider energy system

The total energy storage capacity, E_T is employed to determine the total CO₂e emissions and primary energy expended, E_e used by utilising energy vector parameters such as the energy expended and emission factors.

3. Model parameters

3.1. Vehicle parameters

In this study a heavy duty truck was evaluated, vehicle parameters are presented in Table 1.

3.2. Vehicle duty cycle parameters

In this analysis, the heavy duty vehicle was assumed to have been driven over the World Harmonized Vehicle Cycle (WHVC) shown in Fig. 3. This cycle is repeated until the vehicle has travelled the distance (range) shown in Table 1.

Table 1
Vehicle parameters.

Vehicle type	Heavy-duty
Base mass [kg]	7350 [18]
Range [km]	500
Aerodynamic coefficient [–]	0.7 [18]
Vehicle frontal cross sectional area [m ²]	4.65 [18]

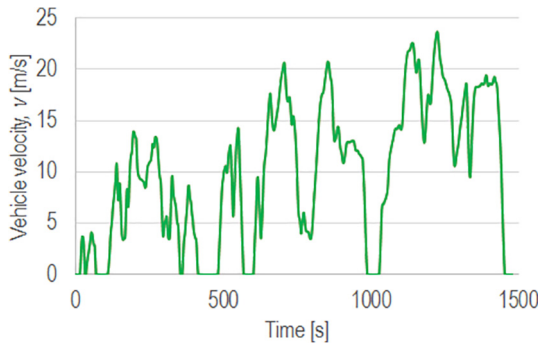


Fig. 3. Vehicle duty cycle used in the analysis.

3.3. Energy vector parameters

Presented in Table 2 are the various energy vector related parameters employed in the analysis. The data for the energy expended, E_e [MJ/MJ final fuel] represent the ratio of the total energy used to obtain and distribute the energy vector to the fuel tank, these were obtained by the EU CONCAWE consortium [19]. The analysis reports the total energy consumption at the production and conditioning at source, transformation at source, transportation to market, transformation near market (final refining), conditioning and distribution across multiple energy sources and pathways. Representative EU standard diesel and gasoline have been considered, electricity was assumed to be obtained from the 2014 EU grid mix as this is the source for electricity for the BEV. The most effective and technically feasible source of low-carbon hydrogen is currently derived from thermal reforming of natural gas with carbon capture technology (CCS) and this is labelled as hydrogen (thermal), finally hydrogen from electrolysis (labelled as green hydrogen) obtained from excess wind energy was also considered.

3.4. On-board storage parameters

In an effort to account for the challenges of alternative fuel/powertrains options a full range of on-board vehicle energy storage systems were considered in this analysis. As a means to simplify the analysis a set of parameters for a fully filled or charged storage system normalised by the total recoverable energy stored are presented in Table 3. This metric accounts for the energy density of fuel, shown in Table 2 as well as the required size and mass of the on-board storage system. The storage systems considered in this analysis were diesel and gasoline fuel tanks, compressed hydrogen (data from U.S. DoE Targets for 2020 [22]) and electric batteries (Lithium-Ion) [23]. Diesel and gasoline are stored in liquid phase and only require a sealed tank at atmospheric pressure, as a result on an energy basis they are an order of magnitude more compact and lightweight than high pressure hydrogen tanks.

The electric battery has been assumed to have a round trip efficiency of 0.95 [24], whereas the other storage systems have been assumed to offer 100%. Other major differences include charging/refuelling times, these obviously increase with the tank size and are only approximated here for completeness. Nevertheless they are considerably more attractive for diesel, gasoline and hydrogen. Estimating battery charging times is more complex with an estimate of the required

Table 3

Parameters representing the various on-board energy storage system.

Energy storage system	Gravimetric	Volumetric	Round trip	Refuelling
	density [MJ _{energy} /kg _{system}]	density [MJ _{energy} /l _{system}]	efficiency [–]	time [min.]
Diesel tank	39.3	35.3	1.0	2–3
Gasoline tank	43.0	32.9	1.0	2–3
H ₂ tank (700 bar)	5.4 [22]	3.6 [22]	1.0	3–5 [22]
Electric battery	0.612 [23]	1.08 [23]	0.95 [24]	30–120+

time to charge a function of the rated power of the charging system, size of battery and current state of charge.

3.5. Transmission, powertrain and on-board energy conversion device parameters

In this analysis, multiple powertrain architecture layouts were considered and a summary of those adopted are presented in Table 1. A range of energy conversion devices are included in the analysis:

Internal combustion engine (ICE): ICEs convert a gaseous or liquid fuel source into rotary energy that is used via a gearbox and transmission system to rotate the wheels. Presented in Table 4 is are the losses observed in a conventional transmission system and the typical idling losses.

Free-piston engine generator (FPEG): A recent design by Newcastle University [25], underpinned by a proof of concept prototype has been used to obtain the technical data presented in Fig. 4 and to populate Table 4. The data used to determine the system volume and mass were obtained by developing the prototype [25] and the efficiencies from Jia et al. [26]. These have been cross compared to data obtained in similar FPEG research carried out by Toyota [27] who have a 11 kW prototype operating at 42% thermal efficiency.

Fuel cell generator (FC): A FC converts hydrogen mixed with air into electricity. It must be supported with the typical architecture of an EV but with a smaller battery to support the intermittent load profiles of a vehicle.

Powertrain properties are summarised in Table 4. EV powertrain components have been sized based on the U.S. Department of Energy electric powertrain design target parameters (2020) [28].

3.6. Vehicle powertrain options

The following powertrain options have been adopted and are summarised in Fig. 5.

3.6.1. Conventional powertrain options

Similar to the powertrain layout shown in Fig. 1a, for context and comparison, conventional solutions with diesel fuelling were analysed Internal Combustion Engine – Compression Ignition Direct Injection – Diesel (ICE-CIDI-Diesel). These were extended to evaluate the potential of a hydrogen fuelled internal combustion engine Internal Combustion

Table 2

Energy vector parameters.

Fuel	Diesel	Gasoline	Electricity (EU)	Hydrogen (Thermal)	Hydrogen (Green)
Energy density [MJ/kg]	41.76	45.72	N/A	119.88	119.88
Mass density [kg/m ³]	845	720	N/A	0.8988	0.8988
Specific energy expended [MJ _{total} /MJ _{fuel}]	0.2 [19]	0.18 [19]	2.07 [19]	1.36 [19]	0.87 [19]
Emissions factor [g CO ₂ e/MJ]	17.23 [20]	18.51 [20]	136.0 [19]	11.9 [21]	4.2 [21]

Table 4
Powertrain Component Parameters.

	Energy conversion efficiency [–]	Gravimetric power density [kW/kg]	Volumetric power density [kW/l]
<i>Electric powertrain components</i>			
Inverter	0.97 [24]	14.1 [28]	13.4 [28]
Motor	0.95 [24]	1.6 [28]	5.7 [28]
EV transmission system	0.95 [24]	1.44 [28]	4.0 [28]
<i>Mechanical systems</i>			
Conventional transmission system	0.99	1.77 [29]	3.8 [29]
Idling losses	0.40	–	–
Internal Combustion Engine – Diesel (–H ₂)	0.47 [3] (0.45 [30])	1.04 [31]	0.48 [31]
<i>On-board electrical generators</i>			
Conventional Range Extender (gasoline)	0.38 [5]	0.43 [5]	0.46 [5]
Rotary engine	0.32–0.35 [32]	0.28 [33]	0.40 [33]
Free-piston Engine Generator (FPEG)	0.50 [26] [34]	0.83 [25] [34]	3.2 [25] [34]
Hydrogen Fuel Cell	0.55 [24]	0.65 [35]	0.65 [35]

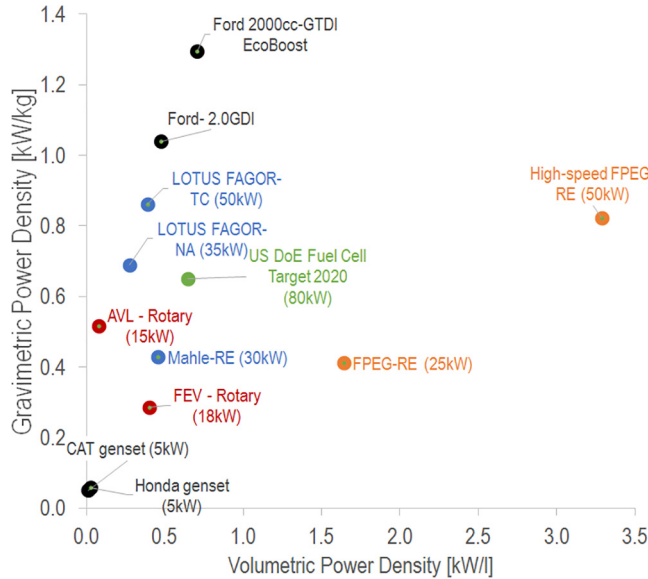


Fig. 4. Comparison of Various on-board electrical and mechanical generators. Labels: CAT genset (5 kW) [36] – a gasoline fuelled micro generator set; Honda genset (5 kW) [37] – a gasoline fuelled micro generator set; Ford 2.0 litre – GTDI EcoBoost [31] – a state-of-the-art diesel engine (without an electrical generator); Ford 2.0 litre – GDI [38] – a state-of-the-art gasoline engine (without an electrical generator); Lotus FAGOR-TC (50 kW) [4] [39] – Turbo-charged gasoline range-extender; Lotus FAGOR-NA (35 kW) [4] [39] – naturally aspirated gasoline range-extender; AVL-Rotary (15 kW) [40]; FEV-Rotary (18 kW) [33]; Mahle-RE (30 kW) [5]; Fuel Cell Target 2020 (80 kW) [35]; FPEG-RE (25 kW) – a 4 cylinder 25 Hz variant of the FPEG presented in [25]; High-speed FPEG-RE (50 kW) – a 4 cylinder 50 Hz variant of the FPEG [25].

Engine – Compression Ignition Direct Injection – Hydrogen (ICE-CIDI-H₂).

ICE-CIDI-Diesel: A conventional internal combustion engine powered by conventional diesel fuel operating in compression ignition direct injection mode.

ICE-CIDI-H₂: A conventional internal combustion engine powered by hydrogen fuel. Due to its abundance and lower costs, the hydrogen is assumed to have been derived from thermal reforming of natural gas

with any excess CO₂ captured and stored in national carbon capture and storage infrastructure. Hydrogen for use in hydrogen fuelled ICE (and fuel cell powertrains) could also be generated via on board reforming of methane or Diesel as described in [8,41], although this technology option is not considered in the current paper

3.6.2. More electrified powertrain options

Hybrid electric vehicles and range extender electric vehicles similar to the powertrain layouts presented in Fig. 1b and c respectively were considered with gasoline and hydrogen fuelling with conventional internal combustion engine and the more compact and lightweight free piston engine generators respectively.

HEV-ICE-gasoline: A hybrid electric vehicle powered by an conventional (reciprocating) internal combustion engine with conventional gasoline fuel.

HEV-FPEG-gasoline: A hybrid electric vehicle powered by an internal combustion free-piston engine generator with conventional gasoline fuel.

HEV-FPEG-H₂: A hybrid electric vehicle powered by an internal combustion free-piston engine generator with hydrogen fuel. As above, the hydrogen is assumed to have been derived from thermal reforming of natural gas with any excess CO₂ captured and stored in national carbon capture and storage infrastructure.

3.6.3. Powertrain options with zero tailpipe emissions

Finally those powertrain options which offer zero tailpipe emissions were considered including;

BEV-electric grid: Similar to the configuration shown in Fig. 1d, a battery electric vehicle (BEV) powered by the UK national electric grid.

HEV-FC-H₂: Similar to the configuration shown in Fig. 1e, a hybrid electric vehicle powered by an fuel cell electrical generator with hydrogen fuel. As above, the hydrogen is assumed to have been derived from thermal reforming of natural gas with any excess CO₂ captured and stored in national carbon capture and storage infrastructure.

4. Model results

4.1. System energy conversion efficiency

The results of the analysis are presented in Fig. 6. The model computes the tank-to-wheel efficiency for each powertrain is shown in Fig. 6a, the BEV offers an > 80% efficiency, a FC system ~50%, conventional powertrain solutions a typical < 15% efficiency, whereas hybrid powertrain solutions offer efficiencies in the ~30–40% range.

However, efficiency of a generator on board a vehicle should also account for the cost of carry the fuel and powertrain systems. As such, a similar analysis is presented in Fig. 6b, results are shown in terms of the amount of energy that needs to be carried to travel a single kilometre. Whilst the conventional powertrain solutions are less favourable, the hybrid powertrain solutions are more on parity with the BEV and FC powertrain solutions.

For hydrogen powered powertrains, the additional mass required for a hydrogen fuel tank increases the vehicle mass, thus a greater amount of energy is required to move the vehicle.

The total amount of energy required to complete the journey is presented in Fig. 6c. This is the cumulative amount of energy required by the vehicle to complete the journey using the powertrain employed, this also corresponds to the total amount of on-board storage capacity. As shown, the total energy required to complete the journey using an BEV is most favourable and least favourable using conventional technology.

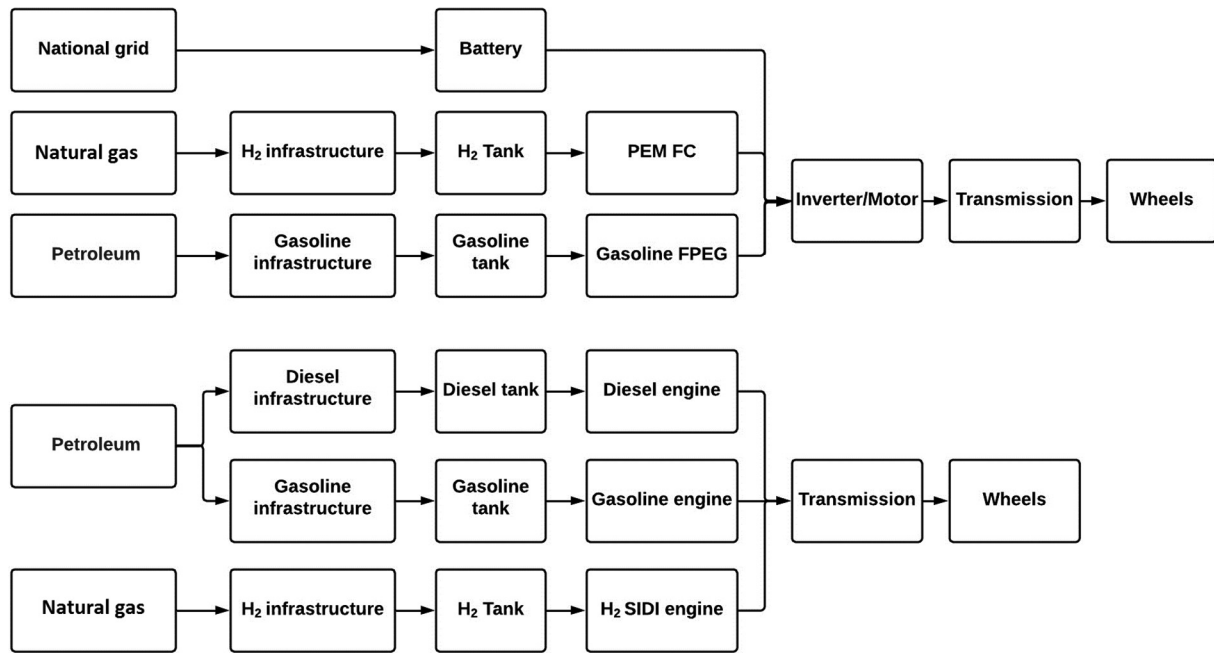


Fig. 5. Various powertrains technology layouts.

4.2. Powertrain, fuel tank size and mass

The impact on the vehicle design is significant for each of the pathways considered. Presented in Fig. 7a and b are the corresponding total powertrain and fuel tank sizes and masses.

As might be expected for a 500 km range, the most heavy powertrain is the BEV with the battery mass itself being the main contribution. Switching to hydrogen fuel means that the use of hydrogen storage tanks make up a significant contribution to the powertrain mass. For example, in the case of a conventional ICE system, the total powertrain system mass is more than doubled over that of a diesel solution.

In terms of system volume, hydrogen fuel tanks and batteries add significant volume to the powertrain. However, across the technology set, advanced hybrid-electric powertrains are more lightweight and compact than FC technology. The most favourable technology is a gasoline fuelled FPEG where a lower system efficiency compared to a FC (and requirement for a larger and heavier fuel tank) is offset by a lower overall system mass and volume.

The overall comparison is presented in Fig. 8a. It would be expected that the most favourable solution from an end user perspective would be in the bottom left hand corner of the diagram with the least favourable options on the top right.

4.3. System mass and volume

The second major parameter to consider for a vehicle is the required system mass and volume to achieve the target performance. As presented in Fig. 8a is the total size of the powertrain per unit of distance travelled. The more favourable solutions from a vehicle design and operator perspective would be toward the bottom right of the diagram. This is even more pertinent for the freight sector where more on-board space yields a greater amount of revenue. This diagram highlights the challenge of de-carbonisation as the fossil based fuelling technologies are most favourable.

4.4. Cost to society

Finally, from a societal and policy maker perspective, the impact of the journey on the wider system is presented in Fig. 8b in terms of net

CO₂ (well-to-wheel) and total primary energy consumed. The underpinning emissions data are detailed in Table 2. These data have been derived from the required energy to produce/generate and distribute the fuel used on-board the vehicle. With such large on-board storage demands for BEVs for a 500 km vehicle range, the results again highlight the significant degree of electric grid decarbonisation required to derive positive benefit from vehicle electrification. Furthermore, whilst both hydrogen technologies did offer lower CO₂ emissions than their fossil fuel equivalents, this is somewhat offset by heavier powertrains/fuel tanks thus overall CO₂ emissions savings are relatively small.

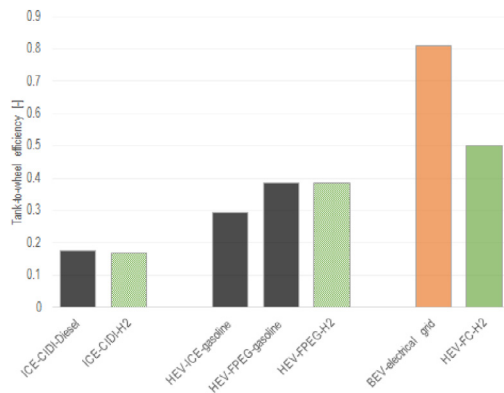
5. Sensitivity to vehicle range

Presented in Fig. 9a and b are the gravimetric and volumetric densities for the powertrain required for the vehicle to operate at ranges of 100 km to 500 km. In both cases, as the vehicle range is reduced, the size of the on-board energy storage reduces and the powertrain can be lighter and more compact.

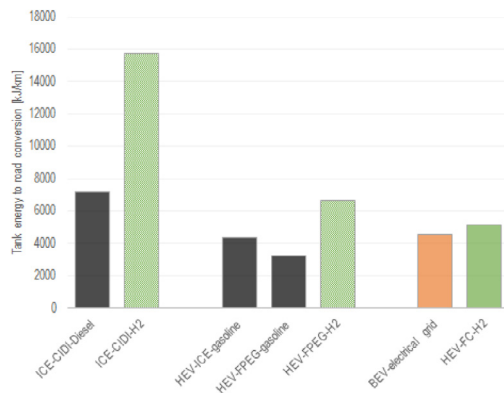
Across all powertrain configurations, the influence of additional vehicle range changes non-linearly. There are multiple factors involved but the most critical is how on-board energy storage scales upward. It is clear that liquid hydrocarbon fuels continue to offer the most favourable solution as range is increased. Whilst BEV and to a lesser extent hydrogen energy storage solutions offer positive improvements with increasing range out to 250 km range, beyond this point little added value is offered.

The results of the same analysis are presented in Fig. 10a and b in terms of the sensitivity to primary energy usage and carbon dioxide emissions respectively. In this analysis, sensitivities proved linear and thus the sensitivity gradients are presented.

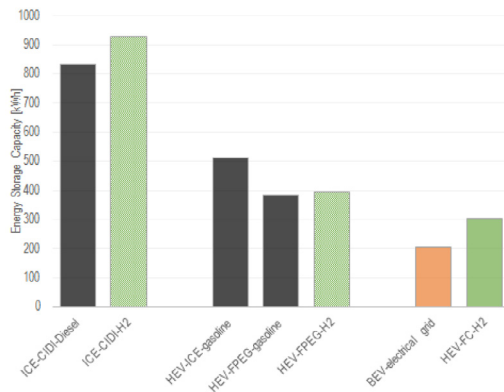
In all cases, as range is increased, mass is increased and more energy is used and therefore more CO₂ is emitted. Noting that sensitivities are presented in a log scale. In general, the ICE-CIDI-H2 and BEV showed most significant sensitivities both due to a significantly increasing storage mass. This resulted in increased primary energy usage and net carbon dioxide emissions.



(a) Tank-to-wheel efficiency



(b) Energy in the tank requirement per distance unit travelled

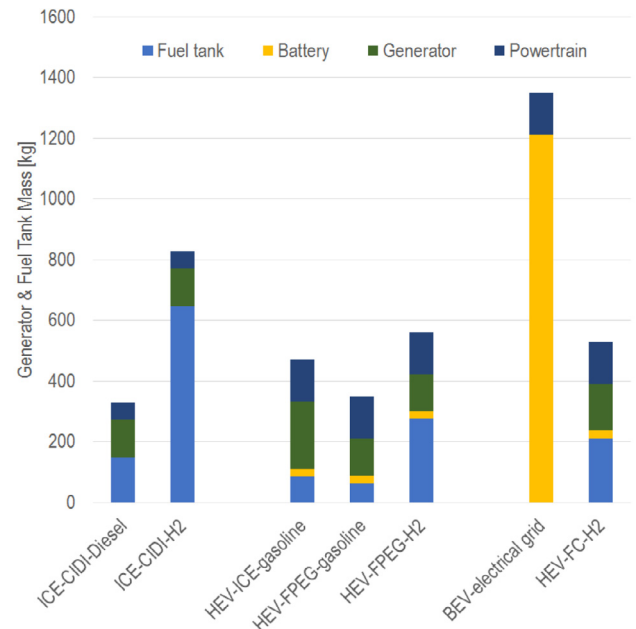


(c) Required total energy storage capacity

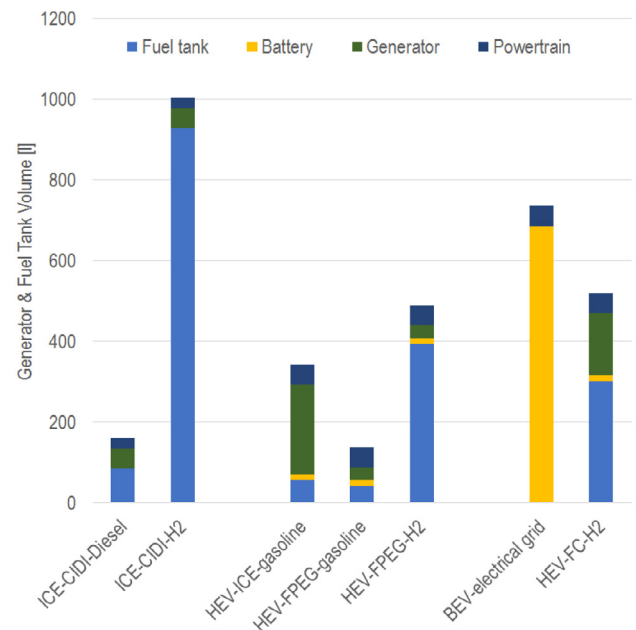
Fig. 6. Analysis of various powertrain solutions for a HDV with 500 km range.

6. Increased electrification through use of REEVs

In terms of the model, there is only a subtle difference between a HEV and a REEV. *i.e.* the relative size of the on-board battery storage capacity compared to the fuel tank storage capacity. There are many relative sizes of REEV possible, however in this analysis, the full range of electrification (0–100%) were evaluated yielding the sensitivities presented in Fig. 11. The results of the analysis in terms of the size and weight of the system as well as the net CO₂ and total energy consumed are shown as a sensitivity as all relationships proved to be linear with



(a) Overall system mass



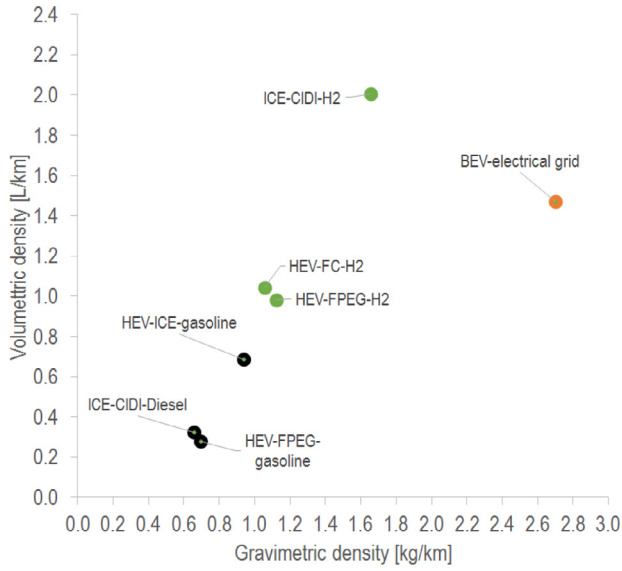
(b) Overall system volume

Fig. 7. Analysis of various powertrain solutions for a HDV with 500 km range.

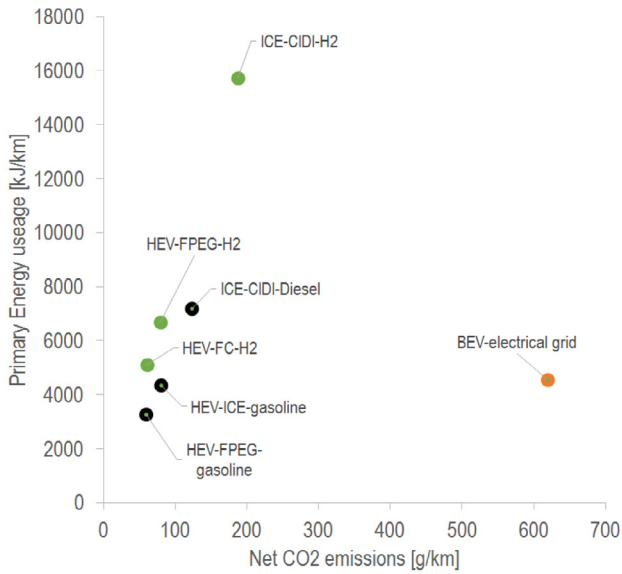
respect to the level of electrification.

In all cases, an increased level of electrification yielded an reduction in gravimetric and volumetric density. The most significant being from the gasoline fuelled range-extendors.

It was assumed that on-board battery was charged using electricity obtained from the UK National Grid. As such, in all cases an increase in net CO₂ was observed with all but the fuel cell increasing the primary energy used to complete the journey.



(a) Volume and mass per unit distance



(b) The cost to society

Fig. 8. Analysis of various powertrain solutions for a HDV with 500 km range.

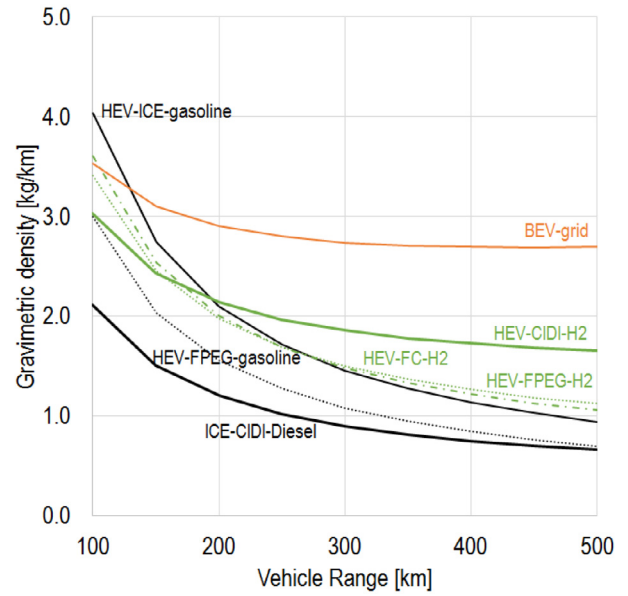
7. Future practical low-carbon vehicle development pathways

Reflecting the reality that both the energy and transportation sectors are currently undergoing change at an unprecedented rate. In this section, a sensitivity analysis is carried out to explore the potential of alternative technological pathways.

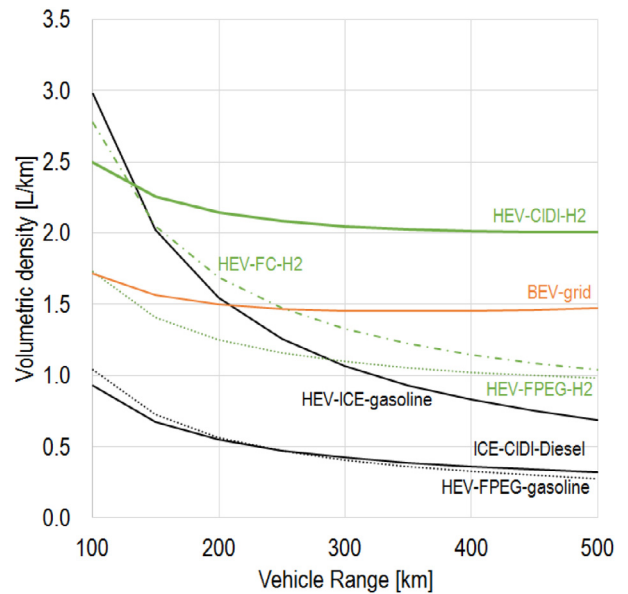
The main pathways considered in this work included;

Advancements in general vehicle design: General advancements in vehicle design are considered including general vehicle light-weighting, improvements to the rolling resistance and aerodynamic improvements.

Further advancements in internal combustion engine design: The overall efficiency of internal combustion engines have consistently improved over the last 30 years. In order to compare with alternative future technological pathways, it is important to estimate any expected advancements in the core technology over equivalent time-scales.



(a) Required powertrain mass per unit of range



(b) Required powertrain volume per unit of range

Fig. 9. Analysis of various powertrain solutions for a HDV with various ranges.

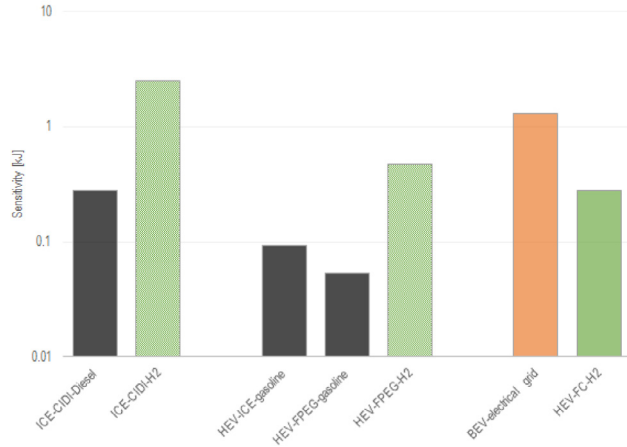
Light-weighting of electrical powertrains: Whilst e-powertrains have a high efficiency, the analysis explores the relative impact of delivering more compact and lightweight designs.

Advancements in range-extender design: The transition toward on-board electrical generation coupled with on-board electrical storage is highly disruptive. Alternative efficiency, gravimetric and volumetric densities are explored, including the potential for future fuel-cell vehicles.

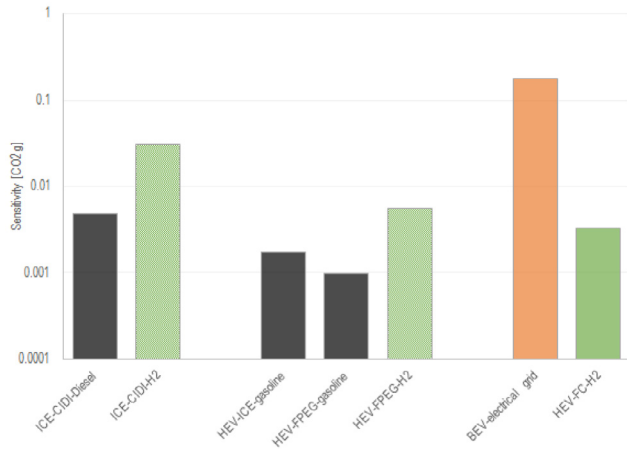
New paradigms for on-board electrochemical battery storage: Rapid development of compact and lightweight batteries based on future designs and materials. Alternative targets are explored.

Advancements in on-board hydrogen storage: A barrier to the deployment of hydrogen fuelled vehicles is the volumetric and gravimetric energy storage density. The impact of advancements in this area is explored.

Toward the de-carbonisation of electricity/hydrogen: The source of



(a) Sensitivity to primary energy usage



(b) Sensitivity to carbon dioxide emissions

Fig. 10. Sensitivity analysis of the various powertrain solutions.

electricity is key to determining the net CO₂ emissions from BEV or REEVs. Alternative energy sources and energy mixes are explored. A 'hydrogen economy' pathway is a key aspect of most de-carbonisation roadmaps and implementation plans. The sensitivity of the analysis to improvements to the efficiency of the hydrogen synthesis process are explored.

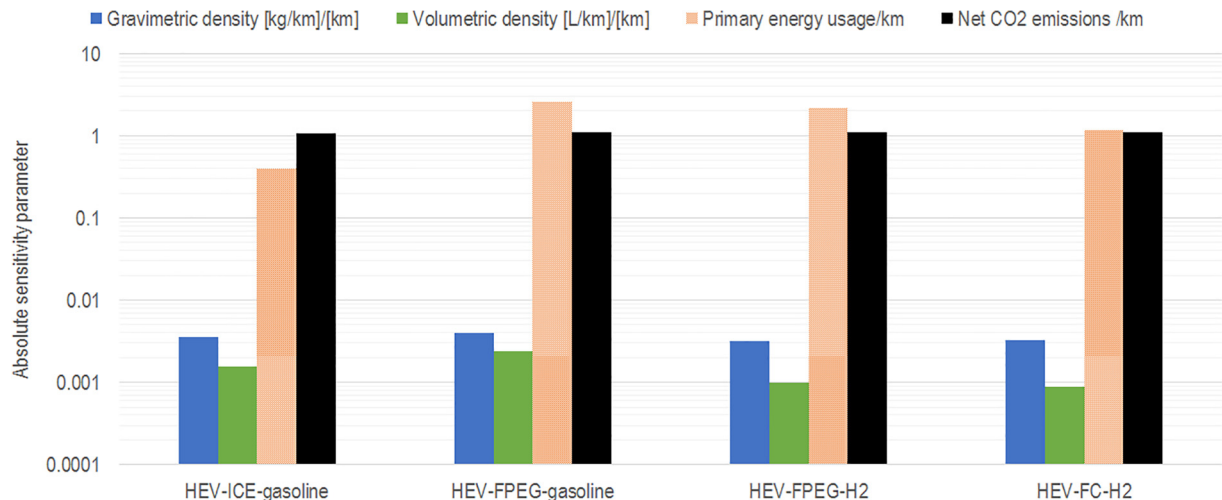
7.1. Advancements in general vehicle design

The influence of general advancements in the vehicle design on the overall primary energy usage and the net CO₂ emissions are considered in this analysis. The vehicle parameters presented in Table 1 have been used as a base case. Improvements are expected to be cumulative and come through;

1. **Vehicle light-weighting:** The development of more lightweight materials, advanced fabrication techniques and design optimisation has the potential to reduce the weight of the base vehicle. The APC Automotive Roadmap [3], based on a 2015 reference presents a target of 10–15% by 2025 and 25–30% by 2035 for transportation vehicles in general (EVs correspondingly lower at 5–7.5% by 2025 and 25–30% by 2035). However the savings expected across the HD vehicle sector are potentially less promising. An analysis by Ricardo AEA [42] indicates that the base by weight of a so called "average heavy duty truck" (again based on a 2015 model) could be reduced by 4.1, 7.4, 8.6, 9.8 and 10.2% by 2020, 2025, 2030, 2040 and 2050 respectively. This is a non-linear relationship but for comparison, this corresponds to an improvement of 0.1–0.2% per year.
2. **Rolling Resistance:** Bridgestone Tyre manufacturers are targeting [43] a 25% improvement of rolling resistance by 2020 relative to a 2005 baseline. Achieving an improvement of 14, 15, 19% in 2015, 2016 and 2017 respectively. This corresponds to an improvement of 2.3% per year.
3. **Aerodynamic improvements:** The development of more aerodynamic vehicles has been a major on-going activity for vehicle design engineers for decades. As such heavy duty vehicles have also the potential for further improvements in this area. Recent analysis [44] across a number of studies has indicated that improvements in the range of 4–18% could be achieved in the 2020–2030 time frame. Across these studies, an improvement of 0.6% per year was typical.

Based on the above relationships and a projection out to 2025 as a baseline an evaluation on vehicle performance for primary energy use and CO₂ emissions is presented in Fig. 12.

As shown, the cumulative effect shows that the design

Fig. 11. Sensitivities of volume, mass, primary energy consumption and net CO₂ to the % electrification of the REEV.

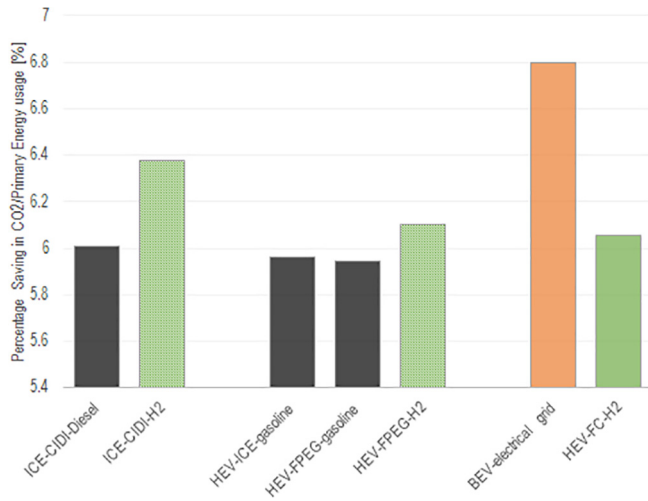


Fig. 12. Percentage saving on primary energy use and CO₂ emissions for each technology in 2025 as a result of projected light-weighting, rolling resistance and aerodynamic design improvements.

improvements outlined to the base HGVs design would be expected to yield a 6–7% improvement in overall fuel consumption and CO₂ emissions even before the vehicle powertrain architecture is modified. The design improvements appear to have the most significant positive impacts on those vehicle types which have the highest energy storage demands and mass.

7.2. Further advancements in internal combustion engine design

The overall efficiency and gravimetric and volumetric density of internal combustion engines have consistently improved throughout its history. Similarly, further improvements would be expected to take place over the next generation of powertrain designs. In recent years, the research and development landscape has started to ask for designs which can achieve thermal efficiencies of more than 55% [3] by 2025 and 60% by 2035 with the challenge of meeting zero emissions in controlled emission zones. This corresponds to a 1.38% improvement in efficiency per year.

Presented in Fig. 13 are the corresponding sensitivities to the impact of these improvements to the overall vehicle design constraints, results presented in terms of primary energy use and CO₂ emissions.

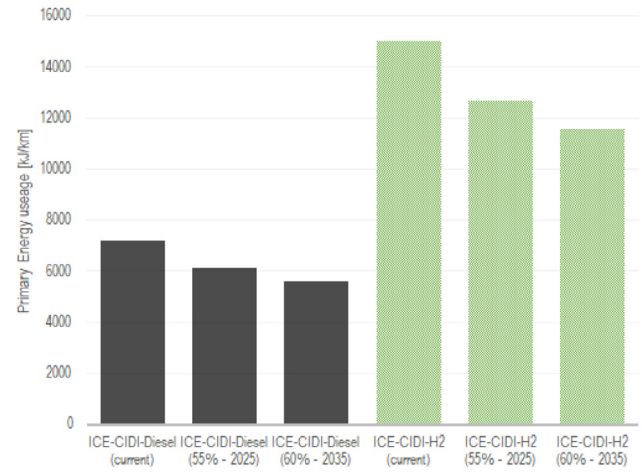
The analysis shows that these efficiency improvements would mean a HD vehicle powered by conventional ICE CIDI engines fuelled by Diesel would be expected to achieve CO₂ emissions of less than 100 g/km by 2035 with a less than 6 MJ/km energy consumption. This would be equivalent to a current passenger car. The impact of this is seen through a) a more efficiency energy conversion and b) thus the need to carry less fuel and less overall mass.

Similar proportional reductions would be observed for hydrogen fuelling.

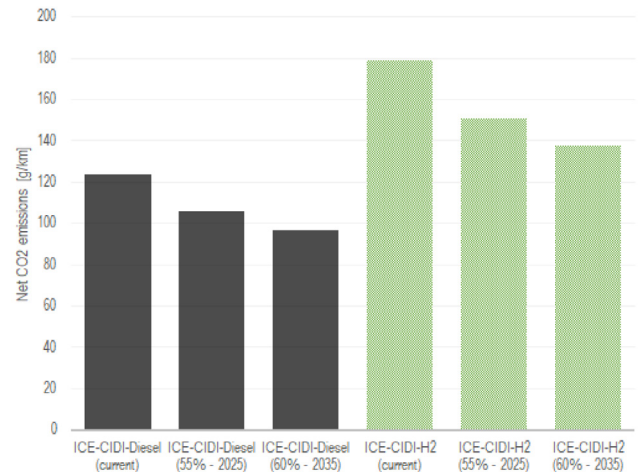
7.3. Light-weighting of electrical powertrains

Improvements in electrical powertrains are expected to be cumulative and come through;

1. **Component efficiency improvements:** As it stands, electrical powertrains are highly efficient (Table 4) compared to the other technologies considered here. The APC Roadmap [3] puts forward the overall efficiency of the drive cycle based on a 2017 baseline as 83%, increasing to 88% and 90% in 2025 and 2035 respectively. This can be approximated as an 2.57% improvement per year based on Worldwide Harmonised Light Vehicle Test Procedure (WLTP).



(a) Sensitivity to primary energy usage



(b) Sensitivity to carbon dioxide emissions

Fig. 13. Sensitivity analysis showing the potential impact of improved internal combustion engine (ICE) thermal efficiency improvements.

The baseline model developed in the earlier section approximates that the overall efficiency of the BEV is 81% and as such not identical to the APC Roadmap [3]. To reflect the improvements expected over the next few years, the expected net improvements to efficiency have been of 5% and 7% by 2025 and 2035 respectively have been employed.

2. **More compact designs:** The APC Technical Roadmap [3] indicates that it is technically feasible to improve electric machine volumetric density from 4.5 kW/l (2017) to 6.0 and 7.0 kW/l by 2025 and 2035 respectively. Again, these are not identical to the baseline analysis and reflect total system values (rather than sub-components shown in Table 4). As a means to reflect the impact of positive design improvements, the percentage improvement has been used to drive the underlying estimation of powertrain size improvement.
3. **More lightweight designs:** The APC Technical Roadmap [3] indicates that improvements to electric machine gravimetric density from 1.5 kW/kg (2017) to 2.0 and 2.5 kW/kg by 2025 and 2035 respectively are technically realistic. The same methods for including these assumptions into the analysis used to estimate the volumetric density have been employed.

Presented in Fig. 14a and b are the results of the analysis in terms of the

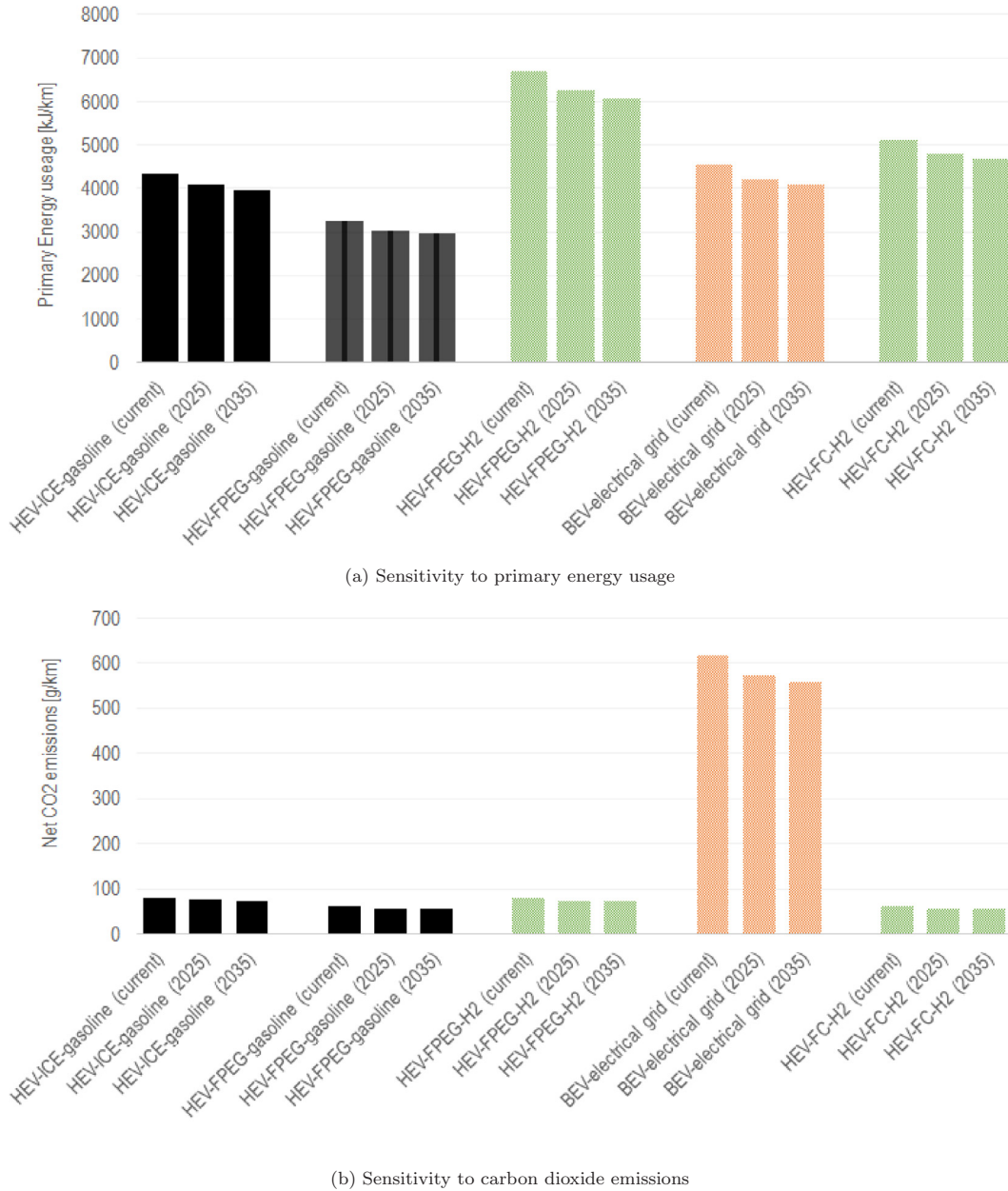


Fig. 14. Sensitivity analysis showing the cumulative impact of improved electric machine design and efficiency in 2025 and 2035.

size and weight of the system as well as the net CO₂ and the total primary energy consumed.

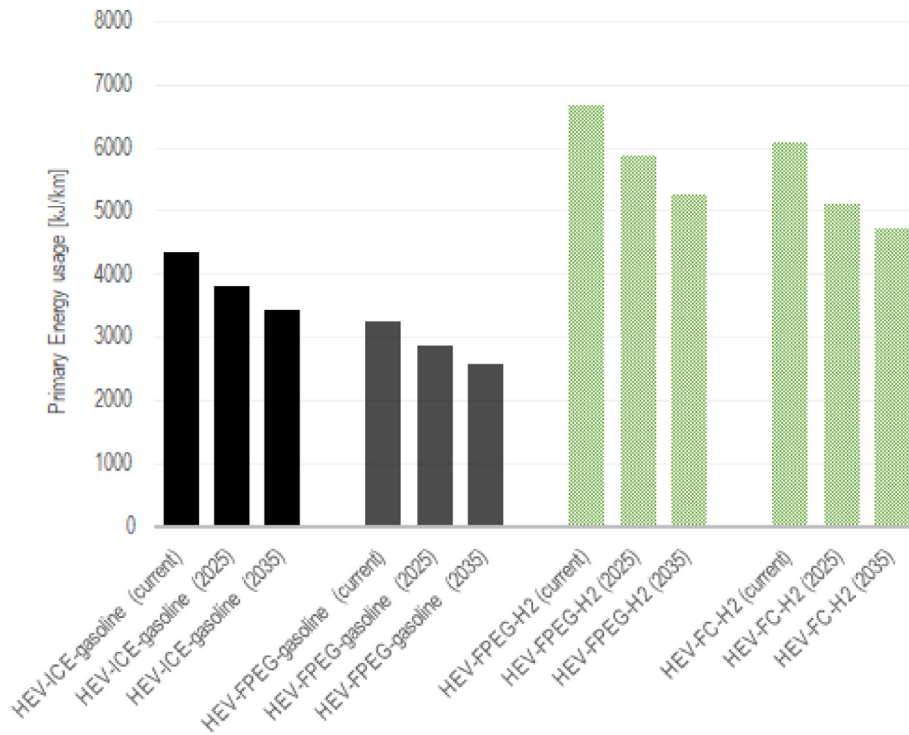
7.4. Advancements in on-board generator design

The transition toward on-board electrical generation coupled with on-board electrical storage is and will continue to be highly disruptive for the transportation sector. Improvements in electrical powertrains are expected to be cumulative and come through;

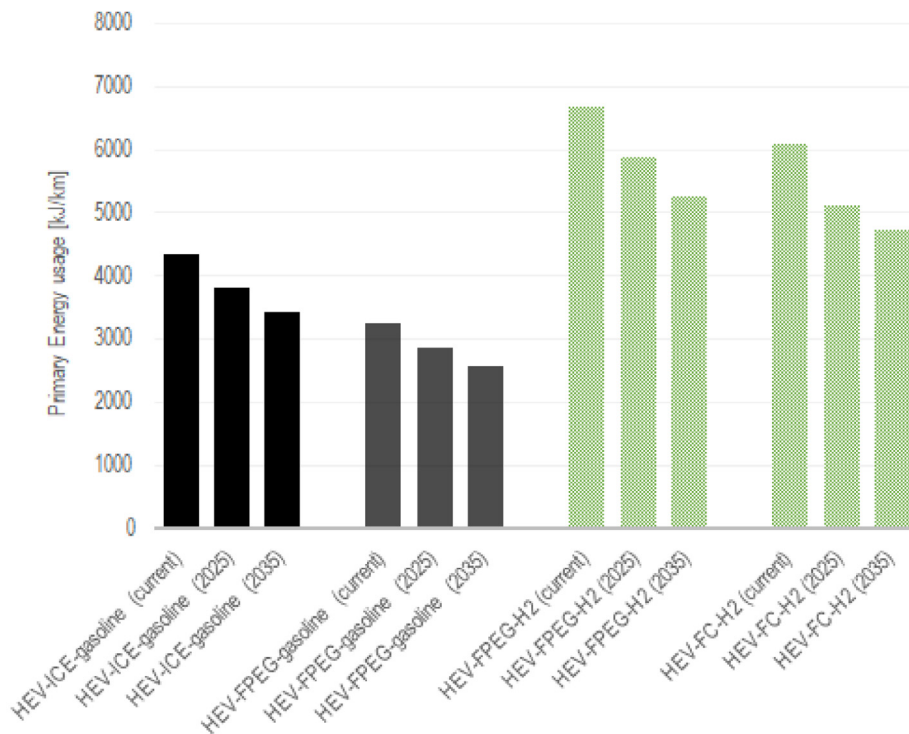
1. **On-board efficiency improvements:** As it stands, on-board generators have the potential for improvement in terms of their system efficiency (Table 4). However, the extent of the improvements are is highly dependent on multiple and complex technical factors such as the underlying technology, its thermodynamic cycle and the underlying technology readiness level (TRL). The APC Technical Roadmaps [3] indicated that a thermal efficiency

of 60% in 2030 would be feasible for Diesel-like engine technologies. It also stated that for an existing baseline of a light-duty gasoline spark-ignition engine could achieve a thermal efficiency of 38%, increasing to 43% and 48% by 2025 and 2035 respectively. In the analysis that follows, these figures will be used directly for the HEV-ICE-gasoline case, the proportional improvements will be used for the HEV-FPEG-gasoline and HEV-FPEG-H2 configurations. For the fuel cell configuration, thermal efficiency improvements based on DoE targets a 65% peak thermal efficiency by 2020 [35] and an ultimate target of 70%. The ultimate target will be associated with the 2035 timescale.

2. **More compact designs:** Similarly improvement for how compact designs can be made can only be considered as technology specific. In the ICE and FPEG applications, the most significant savings will be achieved through the light-weighting of the associated electric machine. Based on the improvements outlined for the electric machine described above and [3], for a FPEG this would be expected to be



(a) Sensitivity to primary energy usage



(b) Sensitivity to carbon dioxide emissions

Fig. 15. Sensitivity analysis showing the cumulative impact of improved range extender design and efficiency in 2025 and 2035.

10% and 15% on a volumetric power basis in 2025 and 2035 respectively. For an ICE with attached motor configuration, this would correspond to be 2.5% and 3.6%. These differences are largely associated with the fact that the crankcase has been eliminated from

the FPEG and therefore the mass and volume of the electric machine take a larger proportion of the whole unit.

A fuel cell target set for 2020 [35] is 0.65 kW/kg also corresponds to the ultimate target and will remain unchanged.

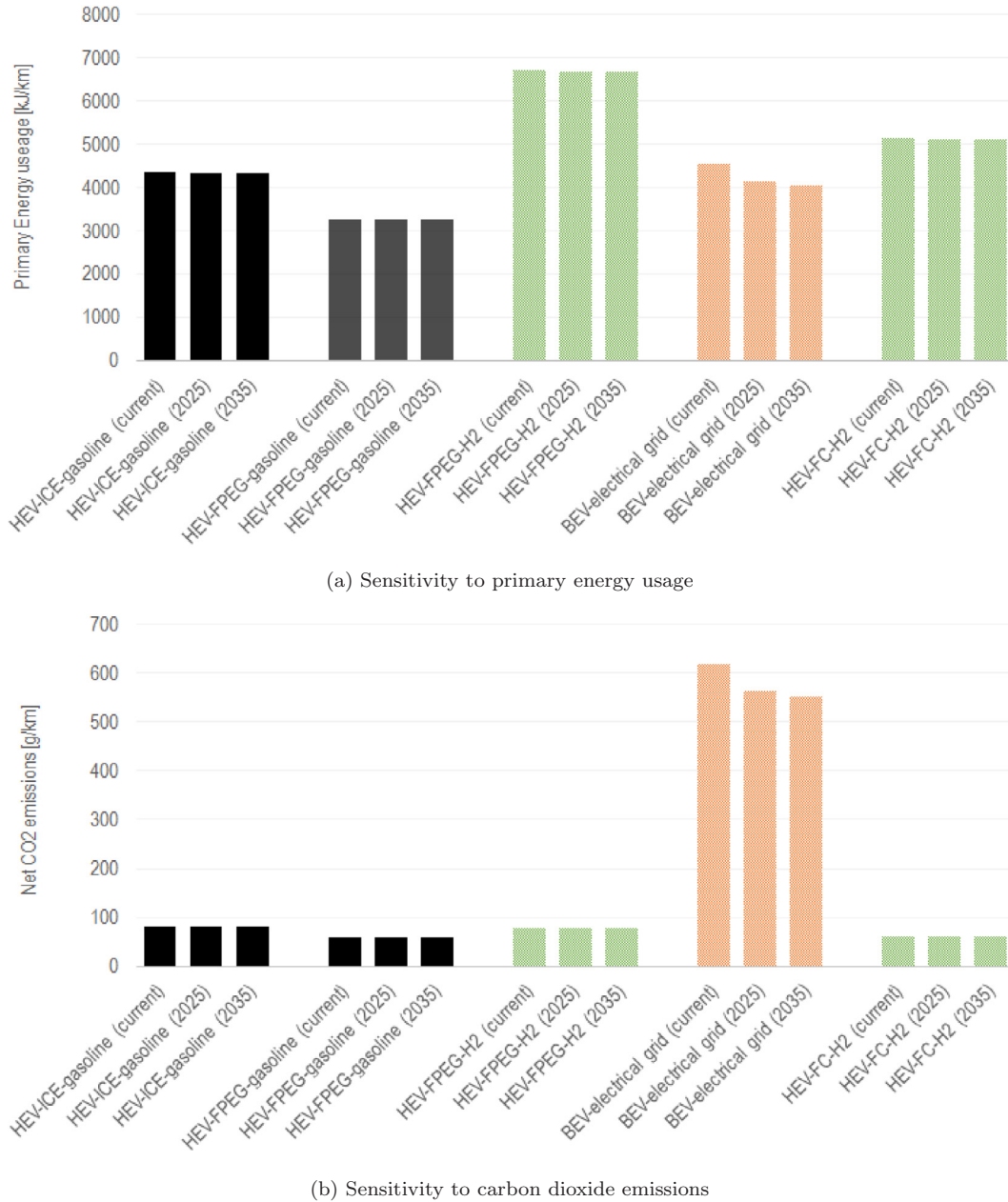


Fig. 16. Sensitivity analysis showing the cumulative impact of improved battery power and energy density in 2025 and 2035.

3. *More lightweight designs:* Based on the APC technical roadmaps [3], a FPEG would be expected to have a 15% and 35% improvement on a gravimetric power density basis in 2025 and 2035 respectively. For an ICE with attached motor configuration, this would correspond to be 7.1% and 11.4% respectively. A fuel cell target set for 2020 [35] is 0.65 kW/l aims to increase to 0.85 kW/l as the ultimate target (2035).

Presented in Fig. 15a and b are the results of the analysis in terms of the size and weight of the system as well as the net CO₂ and the total primary energy consumed.

7.5. New paradigms in on-board battery storage

Recent significant investments into the development of more compact and lightweight batteries means that future estimates on performance and design are uncertain. Advancements in cost, energy and

power density are expected benefiting both BEV and HEV powertrain technologies. The APC Technology Roadmap [3], puts forward targets of a battery pack energy density of 0.28 kWh/l (2017) advancing to 0.55 and 1.0 kWh/l by 2025 and 2035 respectively.

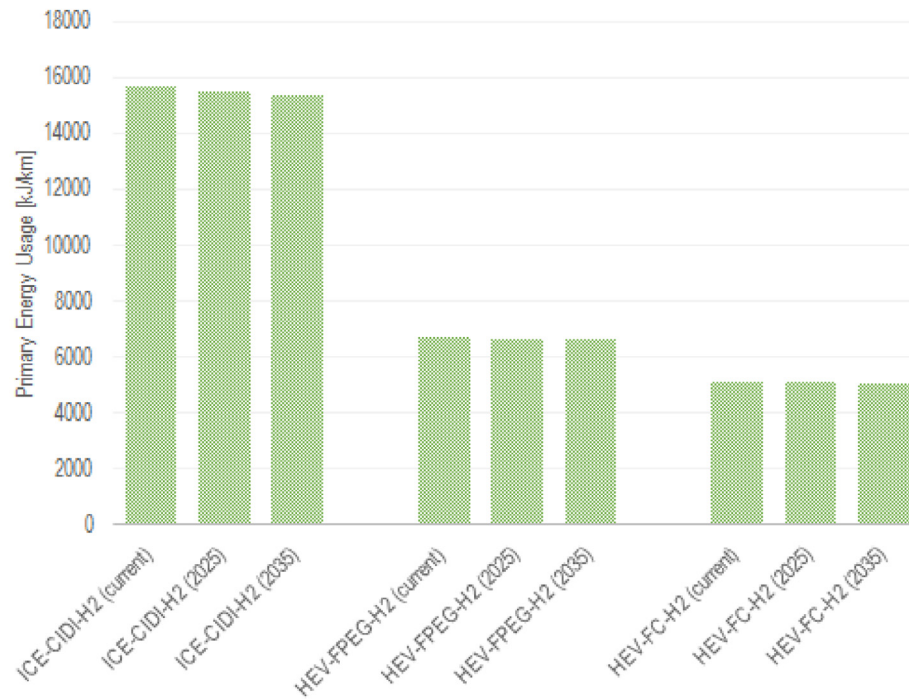
Correspondingly, the battery pack power density is expected to increase from 3.0 kW/kg to 7.5 kW/kg and 12 kW/kg by 2025 and 2035 respectively.

On the basis of these targets, the analysis added proportional improvements (percentage terms) to gravimetric and volumetric density out to 2025 and 2035.

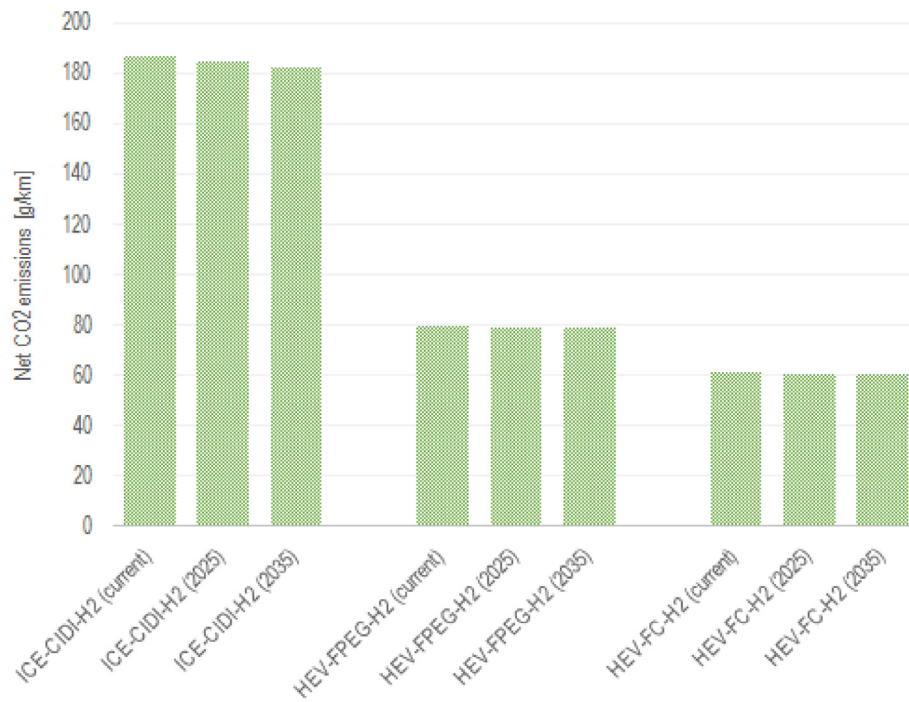
Presented in Fig. 16a and b are the results of the analysis in terms of the size and weight of the system as well as the net CO₂ and the total primary energy consumed.

7.6. Advancements in on-board hydrogen storage

A barrier to the deployment of hydrogen fuelled vehicles is the



(a) Sensitivity to primary energy usage



(b) Sensitivity to carbon dioxide emissions

Fig. 17. Sensitivity analysis showing the cumulative impact of improved hydrogen storage power and energy density in 2025 and 2035.

volumetric and gravimetric energy storage density. The impact of advancements in this area is explored by considering the potential impact of disruptive improvements to storage. Based on a gravimetry density of 5.4 MJ/kg target in 2020 for the whole energy storage system, the US

DoE [22] has set improvement targets of 22% and 44% for 2025 and the future (here considered as the 2035 reference case). Similarly based on a 3.6 MJ/l volumetric density, improvements of 33% and 66% are anticipated by 2025 and 2035 respectively.

Table 5
Parameters representing the different pathways to hydrogen and electricity [19].

Energy vector	Source	CO ₂ emissions	Specific energy expended
		factor [gCO ₂ e/MJ]	[MJ _{total} /MJ _{fuel}]
Hydrogen	Gasified Wood	8.8	1.53
	Natural Gas	72.4	1.32
	Natural Gas + CCS	11.9	1.36
	Coal + CCS	5.6	2.303
	Electrolysis – wind only	4.2	0.94
	Electrolysis – EU mix	226.3	3.92
Electricity	EU Mix	136.0	2.07
	Nuclear	5.0	3.08
	Offshore Wind	0.0	0.12
	Natural Gas + CCS	44.7	1.71
	Medium 2030 target (100 g CO ₂ /kWh)	27.8	–
	High 2030 target (50 g CO ₂ /kWh)	13.9	–

Presented in Figs. 17b and 17a are the results of the analysis in terms of the size and weight of the system as well as the net CO₂ and the total primary energy consumed.

7.7. Toward the de-carbonisation of energy

The source of electricity is key to directly determining the net CO₂ emissions generated from BEV or REEVs. In the analysis above, an estimate based on average electricity grid mix has been carried out. However, this mix is an average with results varying from country to country and the renewable contribution a function of local weather conditions.

In this section, alternative energy sources and energy mixes are explored with respect to their impact on net vehicle primary energy usage and CO₂ emissions. Presented in Table 5 is a list of the key model input parameters associated with the fuel and its source, processing and distribution in terms of energy and CO₂ emissions.

Presented in Fig. 18 are the results of the analysis in terms of the impact on primary energy use and CO₂ emissions.

The baseline for a Diesel fuelled HGV is shown in context with the sources of energy used to power the most favourable hydrogen technology (HEV-H2-FPEG), whilst the magnitudes were not identical, the same trends were observed for all hydrogen fuelled vehicle options. The majority of the analysis carried out in this article considered that hydrogen is derived from Gasified wood, which has similar primary energy usage to conventional Diesel, albeit with less than half the CO₂ emissions. Producing hydrogen from natural gas separation is currently the most common means of obtaining hydrogen, however there is potential for this process to support carbon capture and storage (CCS), which whilst carrying a high energy penalty, it does offer a scaleable solution to powering the Heavy Duty Vehicle (HDV) sector with a relative 40% reduction in CO₂ emissions. This case is also mirrored with coal (with CCS) as the primary energy source, however with a potential 60% reduction in CO₂ emissions.

Two scenarios for hydrogen from electrolysis were also considered with electricity obtained directly from the grid (based on the EU Mix) or from wind energy. Hydrogen derived from electrolysis can support electrical grid supply/demand matching and can offer demand response services during off-peak periods or when excess renewable electricity is available. As such, in this way HGV transport could complement a more renewable electrical energy system. Whilst hydrogen derived from EU electricity would certainly not support a favourable return in terms of energy consumption or CO₂ emissions, such a solution if powered by

excess wind electricity capacity could offer a 83 % reduction in CO₂ emissions.

The sensitivity of alternative forms of electricity for the BEV were also considered. On a primary energy usage basis, all scenarios proved more favourable than those for the Diesel reference and those explored for hydrogen. However on a CO₂ emissions basis, the outcome proved more complex. The results showed that powering an BEV with current electrical grid would not represent a viable solution for reducing CO₂ emissions, even the 2030 grid target (100 g CO₂/kWh) would be unable to match the life cycle emissions of an existing Diesel engine. Only a very challenging 2030 target of (50 g CO₂/kWh) would offer significantly positive CO₂ emissions savings of 54%.

The decarbonisation of the electricity sector can be achieved through the roll out of increasing amounts of natural gas power with CCS, nuclear and wind energy and results are shown to demonstrate the sensitivity to CO₂ emissions. However, they all suffer from the fact that they are inflexible and must be complemented by a combination of grid-scale storage or more flexible energy generation which in itself is typically a high source of CO₂ emissions. Based on the analysis, the most favourable is wind with zero CO₂ emissions, however this source of electricity is typically remote in its location (the analysis was offshore) and very few vehicles will be able to charge directly at the source.

8. Cumulative results

Finally, all the factors outlined above were considered cumulatively to evaluate the characteristics of these alternative vehicle types in 2025 and 2035. As shown in the previous section, the sensitivity to the underpinning energy system is high and as a result, these have not been included in the analysis. The results are presented in Fig. 19.

Whilst the underpinning data considered in the analysis was obtained by consensus across the transportation and powertrain communities, results should be considered to carry uncertainty as many of the technologies currently have no clear technical means to achieve many of the targets. Nevertheless, in all cases, volumetric and gravimetric densities, primary energy use and net CO₂ emissions become more favourable with time.

Only the gasoline fuelled FPEG (HEV-FPEG-gasoline) proved more compact and lightweight than a conventional Diesel engine and fuel tank. All other technologies were significantly less favourable even in 2035.

Other than the hydrogen fuelled ICE (ICE-CIDI-H2), almost all technologies appear to reach a similar gravimetric density by 2035. The targets for battery development are very aggressive and based on these, it would be expected that a BEV powertrain would be more power dense on a volumetric basis by 2035 than all hydrogen powered technology.

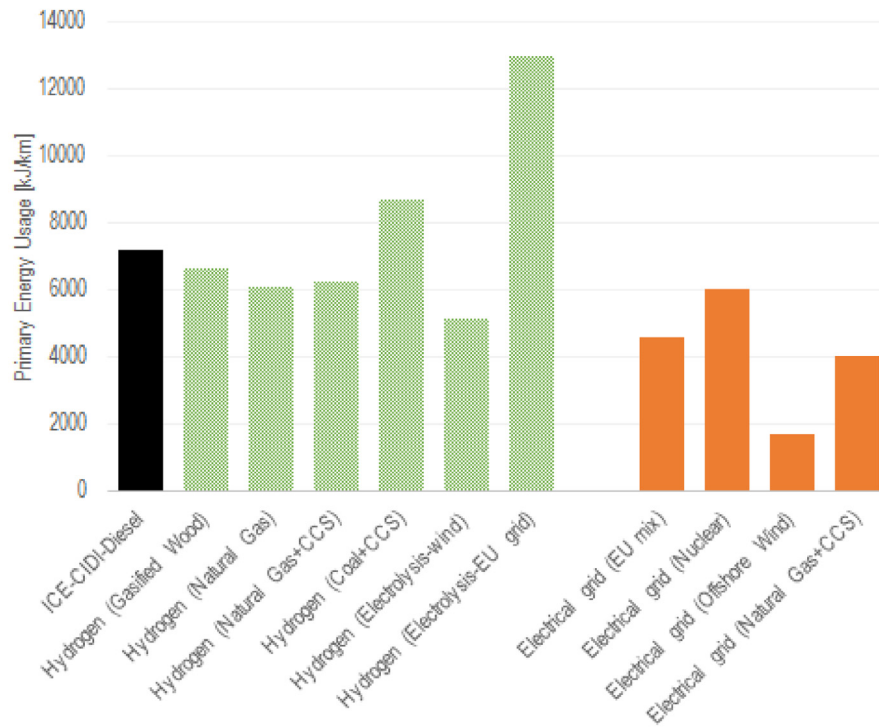
Based on the energy scenarios set-out in Table 2, by 2025 primary energy consumption and net CO₂ emissions would be expected to be better than conventional Diesel powertrains (ICE-CIDI-Diesel) for all technologies other than the hydrogen fuelled ICE (ICE-CIDI-H2) and BEV solutions.

9. Future work

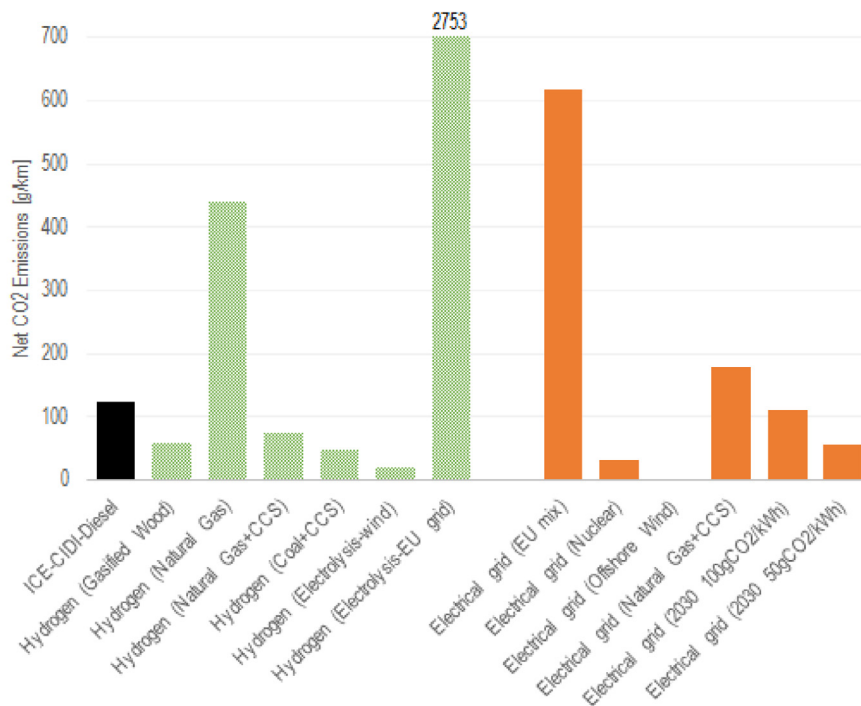
The presented work has shown the potential for this methodology to be applied in exploring alternative technology pathways and their impact on emissions and energy consumption. In the future, the model can be applied to other vehicle types, new and developing technologies, alternative drive-cycles and to explore alternative energy market scenarios. It can also be extended to include cost-based and life-cycle analysis methods and evaluations.

10. Conclusions

A methodology to compare alternative decarbonisation pathways



(a) Sensitivity to primary energy usage



(b) Sensitivity to carbon dioxide emissions

Fig. 18. Sensitivity analysis showing the impact of alternative fuel sources.

for the heavy duty sector has been developed. A target application of a 7.5 tonne vehicle driven over 500 km was used to scale a powertrain system. This analysis offers the following conclusions;

1. The underpinning energy vector and its primary energy source proved to be the most significant factor for reducing primary energy consumption and net CO₂ emissions.
2. A HGV with a BEV powertrain offers no direct tailpipe emissions however carries significantly worse lifecycle CO₂ emissions. Even with a de-carbonised electricity system (100 g CO₂/kWh), CO₂ emissions are similar to a conventional Diesel fuelled HGV.
3. Powertrains with on-board storage with the highest specific density

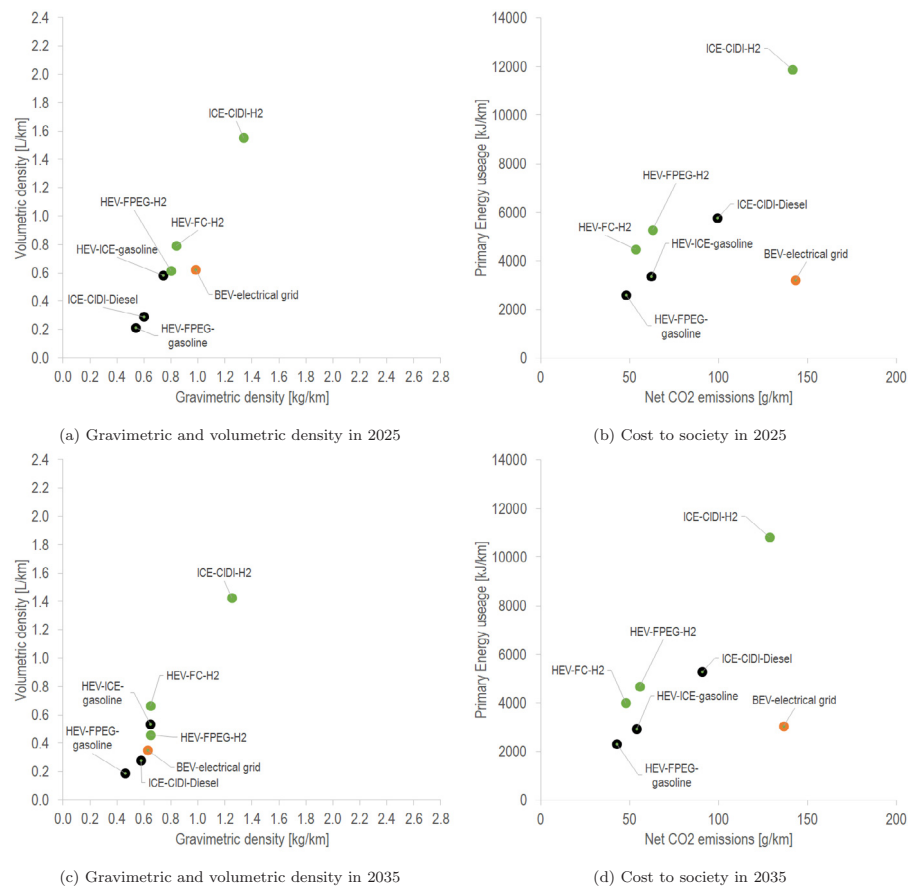


Fig. 19. Indicative volumetric and gravimetric densities, cost to society in 2025 and 2035.

(liquid hydrocarbons) are more favourable for HGVs with longer ranges.

4. Energy source, powertrain technology, on-board storage technology and vehicle duty cycle are heavily coupled and in isolation the development of future powertrain solutions cannot solve the challenge of CO₂ emissions.
5. The cumulative benefits of improved electrical powertrains, on-board storage, efficiency improvements and vehicle design in 2025 and 2035 indicate that hydrogen and electric fuelled vehicles can be competitive on gravimetric and volumetric density.

CRediT authorship contribution statement

Andrew Smallbone: Conceptualization, Methodology, Software, Writing - original draft. **Boru Jia:** Methodology, Writing - original draft. **Penny Atkins:** Methodology, Writing - original draft. **Anthony Paul Roskilly:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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